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S. W. Kahler

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Phillips Laboratory/GPSG
29 Randolph Road
Hanscom AFB, MA 01731-3010

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13. ABSTRACT *(Maximum 200 words)*

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455, L193 (1995).
50. G.M. Simnett, *Space Science Rev.*, **73**, 387 (1995).
51. E. Rieger and H. Marschhäuser, in *Proc. of 3rd MAX 91 Workshop,* eds., R.M. Winglee and A.L. Kiplinger, University of Colorado, Boulder, CO, p. 68 (1990).
52. G.M. Simnett and A. Benz, *Astron. Astrophys.*, **165**, 227 (1986).
53. E.W. Cliver, L.F. McNamara, and L.C. Gentile, *J. Geophys. Res.*, **90**, 6251 (1985).
54. N. Mandzhavidze, in *Proc. 22nd Int. Cosmic Ray Conf.: Invited, Rapporteur, and Highlight Papers,* eds., D.A. Leahy, R.B. Hicks, and D.Venkatesan, World Scientific Pub. Co. Pte. Ltd., Singapore, p. 157 (1994).
55. H. Hudson and J. Ryan, *Space Science Rev.*, **33**, 239 (1995).
56. D.J. Forrest, W.T. Vestrand, E.L. Chupp, E. Rieger, J. Cooper, and G. Share, *Proc. 19th Int. Cosmic Ray Conf.*, **4**, 146 (1985).
57. P.P. Dunphy and E.L. Chupp, in *High Energy Solar Phenomena, AIP Conf. Proc. 294,* eds., J.M. Ryan and W.T. Vestrand, AIP, New York, NY, p. 112 (1994).
58. V.A. Akimov, N.G. Leikov, A.V. Belov, I.M. Chertok, V.G. Kurt, A.Magun, and V.F. Melnikov, in *High Energy Solar Phenomena, AIP Conf. Proc. 294,* eds., J.M. Ryan and W.T. Vestrand, AIP, New York, NY, p. 106 (1994).
59. V.A. Akimov et al., *Solar Phys.*, in press (1996).
60. N. Mandzhavidze, and R. Ramaty, *Ap. J. (Lett.),* **396**, L111 (1992).
61. E.W. Cliver, B.R. Dennis, A.L. Kiplinger, S.R. Kane, D.F. Neidig, N.R. Sheeley, Jr., and M.J. Koomen, *Ap. J.,* **305**, 920 (1986).
62. S.R. Kane, in *Coronal Disturbances, IAU Symp. No. 57,* ed., G. Newkirk, Jr., D. Reidel, Dordrecht, p. 105 (1974).
63. R. Ramaty, R.J. Murphy, and C.D. Dermer, *Ap. J. (Lett.),* **316**, L41 (1987).
64. D.V. Reames, private communication (1995).
65. L.G. Kocharov et al., *Solar Phys.*, **150**, 267 (1994).
66. S.W. Kahler, *Proc. 23rd Int. Cosmic Ray Conf.*, **3**, 1 (1993).
67. E.W. Cliver, *Solar Phys.*, **84**, 347 (1983).
68. J.M. Ryan and M.A. Lee, *Ap. J.*, **368**, 316 (1991).
69. W.T. Vestrand and D.J. Forrest, *Ap. J. (Lett.),* **409**, L69 (1993).
70. E.W. Cliver, S.W. Kahler, and W.T. Vestrand, *Proc. 23rd Int. Cosmic Ray Conf.*, **3**, 91 (1993).
71. R. Moore et al., in *Solar Flares*, ed., P. Sturrock, Colorado Assoc. Univ. Press, Boulder, CO, p. 341 (1980).
72. M. Temerin and I. Roth, *Ap. J. (Lett.),* **391**, L105 (1992).
73. J.A. Miller and A.F. Vinas, *Ap. J.*, **412**, 386 (1993).
74. J.A. Miller and D.V. Reames, these proceedings.
75. J.A. Miller, T.N. LaRosa, and R.L. Moore, *Ap. J.*, in press (1996).
76. J.A. Miller and D.A. Roberts, *Ap. J.*, **452**, 912 (1995).

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Coronal Mass Ejections and Solar Energetic Particle Events

S. W. Kahler

GPSG, Phillips Laboratory
Hanscom AFB, MA 01731-3010

We review the observations relating solar energetic particle (SEP) events to coronal mass ejections (CMEs). Nearly every gradual SEP event is associated with a fast ($v > 400$ km/s) CME, which is presumed to drive a coronal shock that accelerates the SEPs. Evidence supporting the contention that all SEP ions observed in large, gradual events are shock accelerated is reviewed. Evidence for shock acceleration of electrons is found to be more ambiguous.

The following current questions in SEP/CME relationships are discussed: 1. SEP production by electric fields in post-flare loops; 2. the relationship of type II burst shocks and CME-driven shocks; 3. flare impulsive phase contributions to SEP events; and 4. the evidence for shock-accelerated (SA) events; and 5. progressively hardening X-ray spectra and SEP events.

SOLAR FLARES AS SOURCES OF SEPS

The first solar energetic particle events (SEPs) were reported by Forbush (17) as increases in cosmic ray intensities closely following solar flares. In a subsequent work Forbush et al (18) suggested that charged particles could be accelerated to energies of 10 GeV in the variable magnetic fields of flaring sunspots. The SEPs could then escape the sun and reach the earth. Later observations of lower energy (10 MeV) SEP events using riometer observations during the IGY in the 1950s also emphasized the flare associations (65).

A number of investigators subsequently assumed that the energetic protons of SEP events were accelerated in the same flare process that produced energetic electrons. They then used flare centimetric radio data to try to infer the properties of the associated SEP events observed at 1 AU. A detailed account of this early work is given by Kahler (24). Another problem was to understand how the SEPs propagated away from the flare site through the coronal magnetic fields after their production in the flare region. The lack of any correlation between SEP relative elemental abundances and the angular separation from the associated flare site (57) was a serious challenge to models of coronal propagation and suggested acceleration of SEPs by large-scale coronal shocks. The good association of SEP events with metric type II bursts found earlier (73) supported this idea.

INITIAL STUDIES WITH SKYLAB/IMP-7 OBSERVATIONS

The large set of coronal mass ejections observed with the Skylab coronagraph allowed us to study their relationships with both solar flares and SEP events. Although many CMEs were associated with flares, most were not, and a better relationship of CMEs was found with erupting prominences (62). These Skylab results have since been confirmed with SMM coronagraph observations (72).

Kahler et al (28) compared 4-23 MeV SEP events observed on IMP 7 during the Skylab era with the Skylab CMEs. Fourteen of the 16 SEP events with good coronagraph observations could be associated with CMEs. In 11 of 15 cases the associated soft X-ray event was also a long-decay event (LDE). We now understand that LDE events and Hα post flare loop prominence systems (LPS) are the coronal signatures of CMEs as proposed by Kopp and Pneuman (47). It was therefore not surprising that Bruzek (2) had earlier found a good correlation between polar cap absorption events at the Earth, caused by $E >$ 10 MeV protons, and post flare LPS.

Reinhard and Wibberenz (66) had deduced the existence of a "fast azimuthal propagation region" in which SEPs are rapidly distributed over a broad ($\sim 60°$) region of solar longitude. Kahler et al (28) proposed that the SEPs were accelerated in a broad shock, as first suggested by Lin and Hudson (53). The width of the shock could then be understood in terms of the widths of the CMEs driving the shocks. Nine of the 10 CME speeds exceeded 400 km/s, the approximate value of the coronal Alfven speed, and some evidence for a correlation between CME speed and SEP peak flux was found, supporting the shock interpretation.

SOLWIND/IMP-8 COMPARISONS

The Solwind coronagraph on the P78-1 satellite provided a large data set of CME observations over the period 1979-1985. A survey of IMP-8 and ISEE-3 SEP events by Kahler et al (29) showed that 26 of 27 SEP events could be associated with CMEs, confirming the earlier Skylab results. A good correlation ($r = 0.56$) was found between the peak $E > 4$ MeV SEP fluxes and the CME speeds (Figure 1). In addition, the probability of detecting a SEP event associated with a fast CME increased with the CME speed.

Do all fast CMEs produce SEP events? Kahler et al (32) found that 29 of 31 Solwind CMEs with speeds of $v \geq 800$ km/s and considered to be on the frontside of the west limb were associated with SEP events at the Earth. In a similar study with SMM CMEs Kahler (26) found that at least 10 of 11 such CMEs (but with $v \geq 750$ km/s) were associated with $E > 10$ MeV SEP events. Hundhausen et al (22) have presented the speed distribution of the outer loops of CMEs, the structures which should be most relevant for driving shocks (Figure 2). Only about 10% of those speeds exceed 800 km/s.

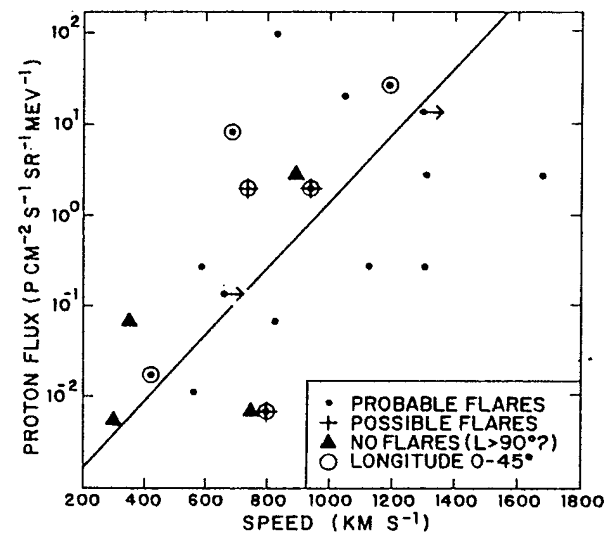

FIG. 1. Plot of the IMP-8 peak 4-22 MeV proton fluxes against the speeds of the associated Solwind CMEs (29). Solid line is the least squares best fit.

However, speeds of CMEs associated with SEP events can extend down to 400 km/s, which is less than the average value of the outer loop speeds.

Kahler et al (29) found that the SEP peak fluxes correlated with CME widths for the 1979-1982 data, but later (32) found no correlation for the widths in the 1983-85 data. The median width of the 11 CMEs of the Kahler (26) study of SMM events was 65°, well above the 44° median of all SMM CMEs. In their survey of CME speeds Hundhausen et al (22) found higher speeds for CMEs with widths above 60°, and Kahler et al (34) also found a correlation between Solwind CME speeds and widths. Thus, CME widths may be an important parameter for SEP fluxes, but perhaps only as a result of the correlation between CME widths and speeds. Some CMEs associated with SEP events lay completely out of the ecliptic plane (29), suggesting either that the shocks extended well beyond the limits of the CMEs or that mid and high latitude coronal field lines extend down to the ecliptic plane. Hundhausen et al (22) found that CME speeds are almost independent of solar latitude, indicating that high-latitude CMEs are not a "weak" form of coronal activity.

SEP events with high $^3He/^4He$ ratios are now known to be distinctly different from the large-flux events with long time scales (63). A comparison of the times of the ^3He-rich events with CMEs showed (30) that there is only a random-chance association of such SEP events with either CMEs or with metric type II bursts, which might be the manifestation of CME- driven coronal

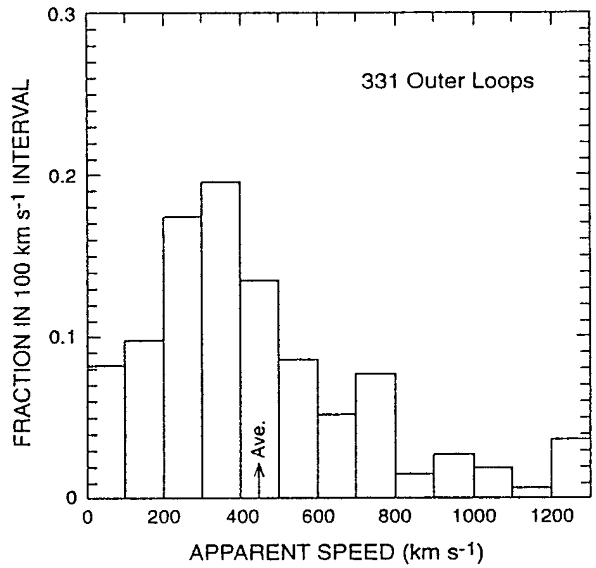

FIG. 2. Speed distribution of SMM CMEs from Hundhausen et al (22).

shocks. These events are now modelled in terms of plasma wave acceleration of the SEPs following wave generation by beams of nonrelativistic electrons (60). CMEs play no role in these models.

SEP EVENTS WITHOUT FLARES

Most gradual SEP events are associated with solar flares, as discussed above. However, if the CME-driven coronal shocks are the means for accelerating SEPs, we should find some cases in which the SEP event is associated with a fast CME, but not with a flare. Kahler (25) examined the risetimes of 15 $< E <$ 44 MeV proton events observed on the GOES spacecraft during the SMM coronagraph observations. Of the 12 SEP events associated with well connected (20°W to 70°W) flares, only three had rise times exceeding 8 hrs. In each of those cases the SEP onset was associated with both a flare and a CME. In at least two of the three cases a second fast CME not associated with flaring activity also occurred and was followed by a substantial SEP flux increase (Figure 3). In those cases the long rise times of the SEP events were due to additional SEP acceleration by shocks driven by the second CMEs.

A simple SEP event associated with a Solwind CME but not with a flare was observed on 5 December 1981 (31). The CME source region consisted of a quiescent filament far from any plage region. The erupting filament

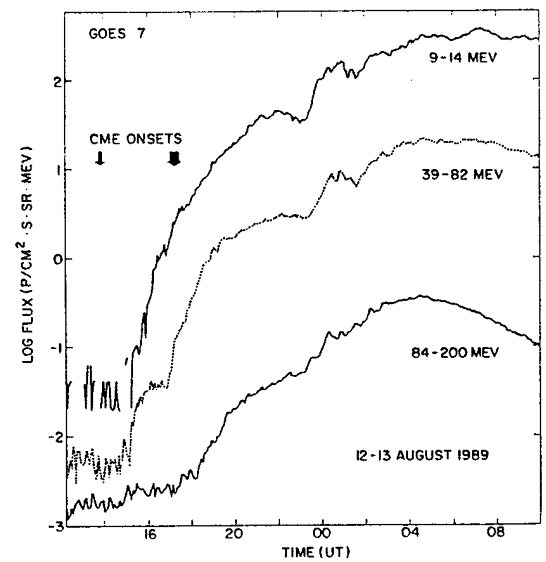

FIG. 3. GOES-7 proton fluxes on August 12-13, 1989 showing the long (17 hr) rise time to maximum (25). Arrows show the times of the two observed CMEs.

could be seen as a bright core in the CME. The gradual disappearance of the filament led to an Hα double ribbon (Figure 4), as expected in the Kopp and Pneuman (47) scenario for a post flare loop system. The proton energies detected at ISEE-3 exceeded 50 MeV in that event. If one considers low energy ($<$ 5 MeV) SEP events, then at least 14 such events associated with solar disappearing filaments instead of large flares have been observed with ISEE-3 particle detectors (67).

RELATION OF CME HEIGHTS AND SEP INJECTION PROFILES

While the previous studies have made clear the association of gradual SEP events with fast CMEs, they did not reveal the spatial and temporal relationships of CMEs with the injection profiles of the SEP events. Kahler et al (35) assumed that SEPs are accelerated on open field lines by CME-driven shocks and asked how the SEP injection profiles varied as a function of CME height. Since the CME height as a function of time was known, the SEP flux profile as a function of time could be replotted as a function of CME height. An important step was to assume that the SEPs propagated with no scattering so that the "solar release times" could be deduced from the flux profiles at 1 AU by using the simple time shift of $dt = 1.3$ AU/v - 8.3 min where v is the

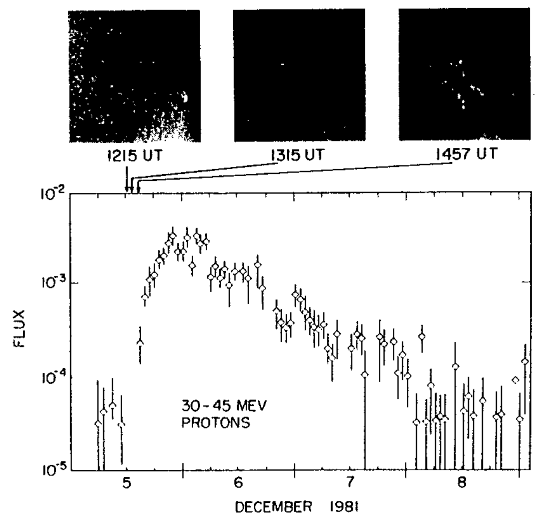

FIG. 4. The Hα erupting filament and SEP event of 5 December 1981 (31). The 0.2 to 2 MeV electron flux profile was similar to that of the 30 to 45 MeV protons.

speed of the SEP and 1.3 AU the assumed path length from the Sun to the Earth. The analysis of 10 SEP events associated with Solwind CMEs showed that at 50 and 175 MeV proton injection profiles are increasing and sometimes reaching maximum when the associated CMEs are at heights of 2 to 10 R$\odot$.

The use of solar release times to determine the SEP injection profiles was justified by Kahler et al (35) on the grounds that several of their events were highly anisotropic while all showed the same qualitative behavior with regard to the CME heights. It clearly was desirable to do the same kind of analysis for SEPs with higher energies and correspondingly longer mean free paths. Kahler (27) did such a comparison using SMM CMEs associated with three ground-level events (GLEs) with associated energies of 470 MeV to 21 GeV. Again, the resulting injection profiles were increasing or reaching peak flux when the leading edges of the CMEs were 5 to 15 R$\odot$ from the sun, as shown in Figure 5. Since this is the "solar" component of SEP fluxes, and the injection occurs in interplanetary space above the closed field regions of the corona, Kahler argued that this result supports the model of a single shock to accelerate both the solar and interplanetary components of SEP events (40).

We have seen from the event shown in Figure 4 that MeV electrons were associated with a fast CME that had no detectable microwave, metric, or hard X-ray signature, suggesting that all the electrons of that event were accelerated by a CME-driven shock. However, we also know that electrons accelerated to tens or hundreds of keV are produced in impulsive flares and escape the sun leaving metric type III burst signatures. Thus, the primary source of an electron event which is associated with both a fast CME and a flare impulsive phase is not easily resolved.

A simple spectral difference between the two kinds of events was suggested by the result of Moses et al (61) that electron events with a single power law in rigidity from 75 keV to 100 MeV were associated with long-duration ($>$ 1 hr) soft X-ray events and those with steeper spectra at low rigidities were generally associated with short-duration soft X-ray events. Since long-duration X-ray events are much more likely than short-duration events to be associated with CMEs, and hence with coronal shocks, a coronal shock origin for the single power-law events was offered (11).

This picture of two basic classes of electron events, one of which is produced in a CME-driven shock, was criticized by Kahler et al (38) for several reasons. First, the median 200 keV flux associated with the shortest duration X-ray flares is only a factor of 3 less than that associated with the longest duration flares, although the latter should include additional shock-accelerated contributions. Second, while very few of the 19 electron events associated with Solwind CMEs should also be associated with short-duration flares and double power-law spectra, nine were so associated. Finally, when the escape efficiencies, defined as the ratios of the peak electron fluxes to the corresponding X-ray fluences (10), are calculated for 30 of the events, the single power-law events have lower, not higher, escape efficiencies. A higher escape efficiency is expected for particles produced in coronal shocks because the lower ambient density of the shock region results in less thin or thick-target X-ray emission. Using this argument to look for evidence of shock acceleration in E $>$ 75 keV electrons, Kahler et al (38) found that the escape ratios of E $>$ 75 keV electron events associated with CMEs were comparable to those without CMEs. They concluded that for nonrelativistic electrons the population of shock-accelerated electrons is at most comparable to the flare-accelerated population.

A different approach to look for evidence of shock-accelerated electrons is to assume that flare-accelerated electrons are injected nearly instantaneously and that the extended duration of any shock acceleration will be reflected in an increase in the rise time of the interplanetary electron event. Thus, the time profile, rather than the peak flux or energy spectrum, is considered the diagnostic parameter of shock acceleration. Kahler et al (39) compared rise times of Helios E $>$ 0.3 MeV electron events with Solwind CME observations. Although the statistics were limited to 24 events, a progressive increase in

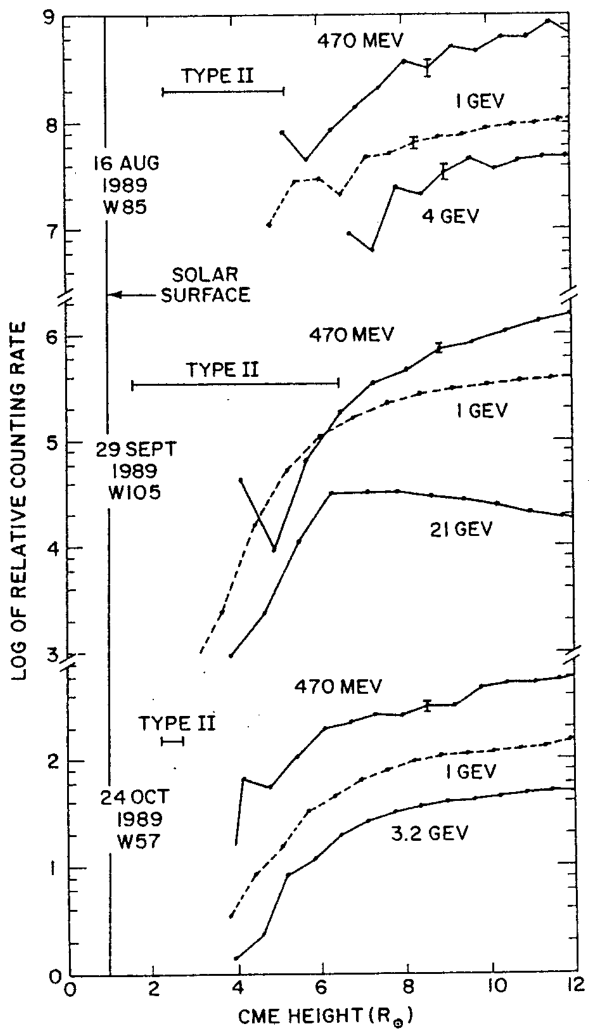

FIG. 5. The proton injection flux profiles of three GLEs as a function of the SMM CME height. Relative counting rates after background subtraction are shown. The 470 MeV fluxes are taken from the GOES HEPAD detector; other profiles are from ground-based neutron monitors. From Kahler (27).

median event rise times was seen for events with i) no CMEs, ii) slow ($v < 800$ km/s), and iii) fast ($v > 800$ km/s) CMEs. A similar result has been found for 15 $E > 0.35$ MeV electron events measured on the Phobos 2 spacecraft (71). These results, combined with those based on escape efficiencies (10,38) suggest that the primary effect of a fast shock is to increase the rise time and perhaps the total number of electrons in the event, but not its peak flux relative to the flare-associated impulsive electrons.

SHOCK ACCELERATION OF ALL SEPS

The argument of Kahler (27) that all the SEPs of a gradual event are accelerated in a single coronal/interplanetary shock implies that the shock must be capable of accelerating ions up to the GeV energies observed in GLEs. The recent result (76) that the mean ionic charge state of Fe at 200 to 800 MeV/nucleon in GLE events is ~14, and hence characteristic of the ambient corona, is strong supporting evidence for this view. Further recent measurements of ionic charge states in 0.5 to 5 MeV/nucleon (58) and 15 to 70 MeV/nucleon (51) ranges support the view that the SEP source is ambient coronal or solar wind material and can not be heated ($T > 10^7$ K) plasmas of flares or reconnection regions. The 21 August 1979 GLE was associated with a fast CME, but the associated flare had a very weak impulsive phase (7), again suggesting that the flare was not the source of the GeV SEPs. That event was one of several large SEP events with weak impulsive phases in the associated flares (8).

Recent shock modelling has suggested that with appropriate conditions SEPs can be accelerated to GeV energies in very short time scales. Ellison and Ramaty (14) assumed a planar shock to model first-order Fermi shock acceleration of electrons, protons, and alpha particles. Using a limited range of shock compression ratios ($r = 1.6$-3), they found good agreement between their model and observations of a number of SEP events, in several cases extending to energies of 10 GeV. With adequate particle scattering from shock turbulence, they found that acceleration to 100 MeV could take as little as 1 sec. Lee and Ryan (50) presented a global time-dependent model for the coronal and interplanetary shock acceleration and propagation of SEPs. By varying the diffusion coefficients, they were able to reproduce the SEP time profiles observed at 1 AU. Zhang et al (81,82) suggested that a time-dependent diffusive shock wave model can explain SEP energies extending to the TeV range. Again, with reasonable diffusion coefficients, they find acceleration to 10 GeV in a time as short as ~ 4 sec. Thus we see that there appears to be no theoretical objection to rapid acceleration of SEPs to relativistic energies by CME-driven shocks in the short time scales required by the GLE observations.

CURRENT QUESTIONS ABOUT SEP ORIGINS

The comparisons of gradual interplanetary SEP events with CMEs has led us to a simple picture in which all the SEPs are produced in a single CME-driven shock which propagates through the corona and interplanetary space. There are, however, several observations which suggest either modifications or serious challenges to this view. These are reviewed in the following five sections.

SEP Production in Post-Flare Loops

To find any alternative sources of SEPs in the corona, we should seek situations in which substantial energy release occurs on or near open field lines. Impulsive flares are an obvious candidate, and these frequently lead to the ^{3}He-rich SEP events discussed by Reames (63). However, eruptive flares, characterized by associated CMEs and post-flare loops, continue to release energy for tens of minutes to hours after their onsets. The view today is that the post-flare loops form during the process of magnetic reconnection of oppositely directed field lines (e.g., (16,15)). The reconnection leads to the reformation of coronal streamers blown open during the preceding CME (37).

The reconnection in post-flare loops sometimes results in gradual hard X-ray bursts characterized by X-ray emission with a gradually hardening spectrum and a large ratio of microwave to hard X-ray emission (9,48). The interpretation is that electrons are accelerated to relativistic energies at the tops of the reconnecting loops (Figure 6) with heights of $> 3 \times 10^4$ km (9). This general picture would explain the continuous acceleration and injection of nonthermal electrons at different altitudes implied by the similarities of gradual hard X-ray and microwave profiles (74) and by the association of hectometric emission with such bursts (44).

Clear evidence for the presence of E > 300 MeV ions in flare gradual phases was found in the γ-ray observations of several large flares in June 1991. A flare on 15 June was found to have an extended phase of pion-decay emission lasting at least 2 hours after the flare onset (1,49). Another flare on 11 June lasted at least 8 hours after flare onset, again with a spectrum consistent with pion decay (41). Similar extended-phase pion-decay events of shorter durations had been seen with the lower-sensitivity detector on SMM (13). While Mandzhavidze and Ramaty (55) favored long-term trapping of particles accelerated during the flare impulsive phase, Kocharov et al (46) and Akimov et al (1) interpreted the events in terms of continuous acceleration of electrons and protons. The delayed emission occurs well after the occurrence of type II bursts (46), and Akimov et al (1) discuss particle acceleration in terms of post-flare loop systems. Martens (56) found that electrons and protons can be accelerated to relativistic energies by the direct electric fields in current sheets overlying post-flare loops. A more realistic model (54) considering

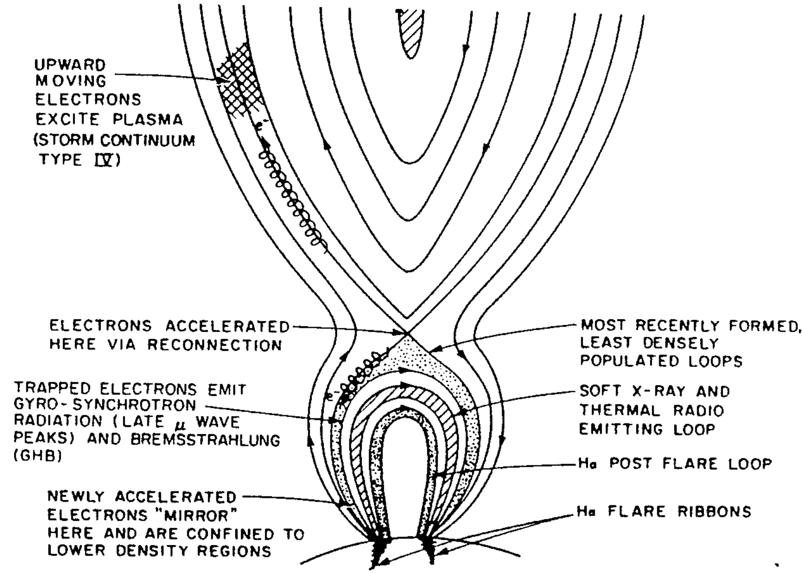

FIG. 6. A schematic configuration of post-flare loops showing the region of electron acceleration in reconnecting coronal fields (9).

the perpendicular magnetic field in the current sheet and the perpendicular electric field outside the current sheet confirms Martens' basic conclusion. The question is whether these very energetic particles observed in the gradual phases can escape to interplanetary space.

Klein et al (45) make the case that noise storms observed for several hours both in the flaring region and several tens of heliographic degrees away following the 19 October 1989 GLE mark the regions of SEP injection into interplanetary space. Since CMEs are typically $\sim 50°$ wide (21), we should expect that the reconnection shown in Figure 6 will occur not only in an active region but also along a magnetic neutral line extending several tens of degrees. A number of such events have now been observed in the Yohkoh soft X-ray images (75,59). Klein et al (45) make the unproven, but plausible, assumption that the electron signatures in these events are also representative of energetic ions. Thus one might expect that a population of energetic ions and electrons would be produced and injected into interplanetary space from reconnecting fields overlying the neutral line. The energetic noise storms, such as those on 19 October or the gradual hard X-ray bursts discussed by Cliver et al (9) generally follow CMEs within one to several hours, so the appearance of any SEPs from the noise storm will be masked by those SEPs generated in the CME-driven shock. Even in the case of the June 1991 extended γ-ray events the time scales of the GLEs appear to be too long to distinguish a second

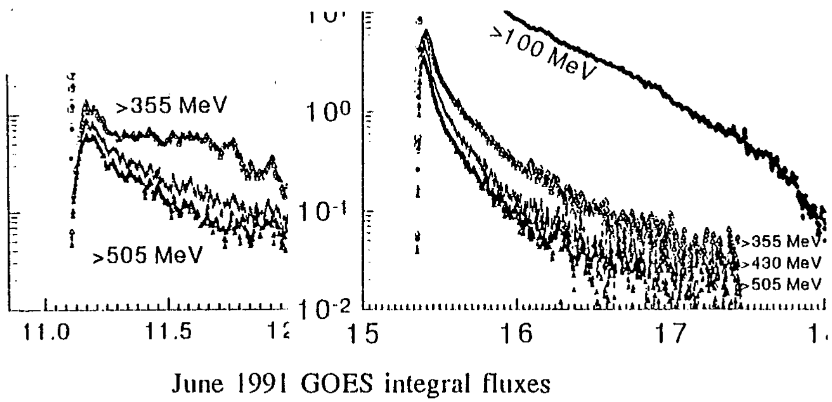

FIG. 7. GOES high-energy integral flux profiles for the GLEs of 11 and 15 June 1991 showing the decay profiles during the extended pion-decay events observed with CGRO and the GAMMA-1 telescope. Adapted from Smart et al (69).

population of SEPs as shown in Figure 7 (69).

Most CMEs are too slow to drive coronal shocks, but all CMEs should be followed by reconnecting fields as shown in Figure 6, so we should encounter at least a few cases in which all the SEPs are injected from the reconnection region and no shock-accelerated SEPs confuse the observations. Such a SEP population would not correlate well with the presence of shocks, but this would seem to contradict the basic observed organization of all SEP events in terms of shocks (5). Although no such ion events have been identified, electron events associated with metric noise storms have been observed. However, both the energies ($E < 10$ keV) and the fluxes of those interplanetary electron events are significantly lower than for electrons observed from flares or interplanetary shocks (52,12). These particles should be confined to the vicinity of the neutral sheet extending above the reforming streamer (20). The positions of those electron streams relative to the heliospheric current sheets have not been studied. It appears that if SEP ions are injected from gradually reconnecting fields following CMEs, the fluxes and energies may be too low to measure easily.

CMEs and Coronal Shocks

The good associations of SEP events with both metric type II radio bursts (73,23) and CMEs suggested that the SEPs are accelerated in coronal shocks driven by CMEs. In that case the type II bursts should be well associated with fast ($v > 400$ km/s) CMEs. The Skylab results (62) supported that

idea, but Wagner and MacQueen (79) suggested that coronal shock waves are produced by flares and propagate through any associated CME. The current view is that type II shocks originate only in flares (3,19), and recent work (78) identifies the beginning of the rapid rise of the first burst of the associated microwave burst as the origin of the shock. Thus the shock driven by the CME, which accelerates SEPs and propagates into interplanetary space, may often be initiated at a frequency too low to be detected on earth (19). This further suggests that MHD models based on the assumption that the interplanetary shock is an extension of the type II burst shock (68,70) may use incorrect boundary conditions. The observational problem here is to distinguish clearly the flare shock from the CME-driven shock. This can only be done by satellite observations in the 2 to 20 MHz band (19).

Flare Impulsive Phase Contributions to Gradual SEP Events

When a gradual SEP event is also associated with a well connected flare, a hybrid event consisting of Fe-rich ions early in the event followed later by Fe-poor ions may be seen (64). In some events the Fe-rich ions reach energies of tens of MeV per nucleon, suggesting that impulsive phase ions are shock-accelerated to the higher observed energies (77,64). The SEP events of 3 June 1982 and 21 June 1980 observed on Helios-1 were unusual in that they were dominated by Fe-rich abundances at $E > 50$ MeV/nucleon throughout each event. They were also associated with impulsive soft X-ray flares, which are generally associated with narrow CMEs (34). Kahler (26) has suggested that the associated narrow CMEs drive correspondingly narrow shocks which may preferentially accelerate the Fe-rich ions near the flare site rather than the ambient coronal material away from the flare site.

If Fe-rich ions from impulsive flares can dominate the SEP fluxes up to 50 MeV/nucleon, can this process take place at GeV energies? Kahler et al (36) discussed this possibility for six GLEs associated with impulsive soft X-ray flares. The presence of type IV radio bursts following 5 of the 6 associated flares suggests that CMEs were associated with those events. However, two recent results raise some doubt about this idea of additional shock acceleration of impulsive SEPs. The first is that Dunphy and Chupp (13) find that the 3 June 1982 and 21 June 1980 flare events were followed by extended phases of high energy γ-ray emission, thus allowing alternative candidate sources for the observed SEP events, as discussed above. The second is that Chen et al (6) find that $^3He/^4He$ ratios of events observed in the 50 to 110 MeV/nucleon range are high ($> .005$) and independent of solar source longitude for 16 events observed on the CRRES mission. In several cases the ratios exceed 0.01 for events associated with eastern hemisphere flares. This result suggests that ^3He enhancement may not arise exclusively in impulsive flares at high energies, contrary to the situation for the low energy (few Mev/nucleon) range.

Shock-Accelerated Events

If electrons are accelerated in coronal shocks, the beams of energetic electrons might appear as fast-drift kilometric bursts originating in the herringbone structure of metric type II bursts. A class of intense, long-duration bursts at 1980 kHz were found by Cane et al (4) to be well associated with metric type II bursts, and became known as shock-associated (SA) bursts. Defining an SA burst as 1980 kHz emission temporally associated with a metric type II burst, but not associated with a metric type III burst, Kahler et al (33) found that nearly half of all type II bursts have associated SA bursts. Using Culgoora Observatory records, they found that the SA bursts corresponded to the most intense features of the metric type II bursts. They also found a generally poor correspondence between the flux profiles of SA bursts and of simultaneous microwave bursts, suggesting that SA emission is not due to energetic electrons escaping from the microwave emission region.

Klein (43) has argued that since all of a group of 12 SA events generally show metric storm continuum or flare continuum during each SA event, electron acceleration and injection occurs over a range of altitudes, including open field lines at the hectometric level, and is not due to shock acceleration. Subsequently, Klein and Trottet (44) found that 5 gradual hard X-ray/radio bursts were also accompanied by hectometric emission similar to the SA events, but not necessarily accompanied by type II bursts. In their view, all the hectometric emission other than type III bursts is due to electron escape from the middle corona and is not the result of large-scale shock acceleration. In our view they have made a good case for electron injection from the coronal gradual events observed in the metric and hard X-ray range. However, their analysis of a small number of very energetic events does not preclude the shock acceleration scenario. It is also possible that electrons accelerated in shocks are not always manifested as herringbone emission. If we accept that protons are accelerated by shocks, then the striking spatial and temporal similarities between 1 MeV electrons and 50 MeV protons found by Wibberenz and Cane (80) in their multispacecraft study suggests shock acceleration of the electrons, as well.

Progressively Hardening X-Ray Events and SEPS

If SEPs are produced only in CME-driven shocks, we do not expect to see any relationship between the SEP event and the hard X-ray burst of the associated flare. Recently, however, Kiplinger (42) has found such a relationship with the $30 < E < 500$ keV X-ray bursts detected by the HXRBS detector on the SMM spacecraft. The characteristic signature for a good association with SEP events is a progressive hardening of the X-ray spectrum either during an individual flux peak or during the burst decay. The analysis used large HXRBS events and asked whether they were associated with observed SEP

events. No inverse study of associations based on observed SEP events was done. An algorithm was developed for the X-ray bursts with which associated SEP events could be forecast with about 95% accuracy. Besides the excellent event correlation, a correlation was found between the FWHM of the longest progressively hardening burst peak and the cube of the peak proton flux of the SEP event.

Progressive spectral hardening of X-ray bursts was one of the characteristics of the gradual hard X-ray bursts studied by Cliver et al (9) and Kosugi et al (48). For those events Cliver et al argued for acceleration and trapping of radiating electrons in post flare loop systems following CMEs. The progressively hardening X-ray bursts of the Kiplinger study (42) were also interpreted as high coronal source regions of particle acceleration, but in addition, as the source of the interplanetary SEPs. If CME-driven shocks are the main source of SEPs, we might expect that SEP events are well associated with post flare loop systems following the CMEs, but the results of the Kiplinger study suggest a much closer relationship between the hard X-ray characteristics of those systems and the SEP events, suggesting that the post flare loops, not the shock, are the primary SEP source.

REFERENCES

1. Akimov, V.V., A.V. Belov, I.M. Chertok, V.G. Kurt, N.G. Leikov, A. Magun, V.F. Melnikov, 23rd ICRC (Calgary) **3**, 111, 1993.
2. Bruzek, A., Ap.J. **140**, 746, 1964.
3. Cane, H.V., and D.V. Reames, Ap.J. **325**, 895, 1988.
4. Cane, H.V., R.G. Stone, J. Fainberg, J.L. Steinberg, and S. Hoang, Geophys. Res. Letters **8**, 1285, 1981.
5. Cane, H.V., D.V. Reames, and T.T. von Rosenvinge, J. Geophys. Res. **93**, 9555, 1988.
6. Chen, J., T.G. Guzik, and J.P. Wefel, Ap.J. **442**, 875, 1995.
7. Cliver, E.W., S.W. Kahler, H.V. Cane, M.J. Koomen, D.J. Michels, R.A. Howard, and N.R. Sheeley, Jr., Solar Phys. **89**, 181, 1983.
8. Cliver, E.W., S.W. Kahler, and P.S. McIntosh, Ap.J. **264**, 699, 1983.
9. Cliver, E.W., B.R. Dennis, A.L. Kiplinger, S.R. Kane, D.F. Neidig, N.R. Sheeley, Jr., and M.J. Koomen, Ap.J. **305**, 920, 1986.
10. Daibog, E.I., V. Kurt, Yu.I. Logachev, and V.G. Stolpovskii, Cosmic Research **27**, 97, 1989.
11. Droge, W., P. Meyer, P. Evenson, and D. Moses, Sol. Phys. **121**, 95, 1989.
12. Dulk, G.A., Sol. Phys. **130**, 139, 1990.
13. Dunphy, P.P., and E.L. Chupp, AIP Conf. Proc. **294** (eds J.M. Ryan and W.T. Vestrand), 112, 1994.
14. Ellison, D.C., and R. Ramaty, Ap.J. **298**, 400, 1985.
15. Forbes, T.G., Geophys. Astrophys. Fluid Dynamics **62**, 15, 1991.
16. Forbes, T.G., J.M. Malherbe, and E.R. Priest, Sol. Phys. **120**, 285, 1989.
17. Forbush, S.E., Phys. Rev. **70**, 771, 1946.
18. Forbush, S.E., P.S. Gill, and M.S. Vallarta, Rev. Mod. Phys. **21**, 44, 1949.

19. Gopalswamy, N., and M.R. Kundu, Coronal Magnetic Energy Releases (eds A. Benz and A. Kruger), 223, Springer-Verlag, 1995.
20. Hirayama, T., Proceedings of Kofu Symposium (eds. S. Enome and T. Hirayama), NRO Report Nbr **360**, 231, 1994.
21. Hundhausen, A.J., J. Geophys. Res. **98**, 13177, 1993.
22. Hundhausen, A.J., J.T. Burkepile, and O.C. St. Cyr, J. Geophys. Res. **99**, 6543, 1994.
23. Kahler, S.W., Ap.J. **261**, 710, 1982a.
24. Kahler, S.W., J. Geophys. Res. **87**, 3439, 1982b.
25. Kahler, S.W., J. Geophys. Res. **98**, 5607, 1993.
26. Kahler, S.W., 23rd ICRC (Calgary) **3**, 1, 1993.
27. Kahler, S., Ap.J. **428**, 837, 1994.
28. Kahler, S.W., E. Hildner, and M.A.I. van Hollebeke, Solar Phys. **57**, 429, 1978.
29. Kahler, S.W., N.R. Sheeley, Jr., R.A. Howard, M.J. Koomen, D.J. Michels, R.E. McGuire, T.T. von Rosenvinge, and D.V. Reames, J. Geophys. Res. **89**, 9683, 1984.
30. Kahler, S., D.V. Reames, N.R. Sheeley, Jr., R.A. Howard, M.J. Koomen, and D.J. Michels, Ap.J. **290**, 742, 1985.
31. Kahler, S.W., E.W. Cliver, H.V. Cane, R.E. McGuire, R.G. Stone, and N.R. Sheeley, Jr., Ap.J. **302**, 504, 1986.
32. Kahler, S.W., E.W. Cliver, H.V. Cane, R.E. McGuire, D.V. Reames, N.R. Sheeley, Jr., and R.A. Howard, 20th ICRC (Moscow) **3**, 121, 1987.
33. Kahler, S.W., E.W. Cliver, and H.V. Cane, Solar Phys. **120**, 393, 1989.
34. Kahler, S.W., N.R. Sheeley, Jr., and M. Liggett, Ap.J. **344**, 1026, 1989.
35. Kahler, S.W., D.V. Reames, and N.R. Sheeley, Jr., 21st ICRC (Adelaide) **5**, 183, 1990.
36. Kahler, S.W., M.A. Shea, D.F. Smart, and E.W. Cliver, 22nd ICRC (Dublin) **3**, 21, 1991.
37. Kahler, S.W., and A.J. Hundhausen, J. Geophys. Res. **97**, 1619, 1992.
38. Kahler, S.W., E.I. Daibog, V.G. Kurt, and V.G. Stolpovskii, Ap.J. **422**, 394, 1994.
39. Kahler, S.W., V.G. Stolpovskii, and E.I. Daibog, Solar Coronal Structures, IAU Coll. **144**, 479, 1994.
40. Kallenrode, M.-B., Adv. Space Res. **13**, 341, 1993.
41. Kanbach, G., D.L. Bertsch, et al, Astron. Astrophys. Supple. Ser. **97**, 349, 1993.
42. Kiplinger, A.L., Ap.J. **453**, 973, 1995.
43. Klein, K.-L., Solar Wind Seven (eds. E. Marsch and R. Schwenn), 635, Pergamon Press, Oxford, 1992.
44. Klein, K.-L., and G. Trottet, AIP Conf. Proc. **294** (eds J.M. Ryan and W.T. Vestrand), 187, 1994.
45. Klein, K.-L., G. Trottet, H. Aurass, A. Magun, and Y. Michou, Adv. Space Res. **17**, (4/5)247, 1995.
46. Kocharov, L.G., G.A. Kovaltsov, G.E. Kocharov, E.I. Chuikin, I.G. Usoskin, M.A. Shea, D.F. Smart, V.F. Melnikov, T.S. Podstrigach, T.P. Armstrong, and H. Zirin, Solar Phys. **150**, 267, 1994.
47. Kopp, R.A., and G.W. Pneuman, Solar Phys. **50**, 85, 1976.
48. Kosugi, T., B.R. Dennis, and K. Kai, Ap.J. **324**, 1118, 1988.
49. Kovaltsov, G.A., I.G. Usoskin, L.G. Kocharov, H. Kananen, and P.J. Tanskanen, Solar Phys. **158**, 395, 1995.

50. Lee, M.A., and J.M. Ryan, Ap.J. **303**, 829, 1986.
51. Leske, R.A., J.R. Cummings, R.A. Mewaldt, E.C. Stone, and T.T. von Rosenvinge, Ap.J. **452**, L149, 1995.
52. Lin, R.P., Sol. Phys. **100**, 537, 1985.
53. Lin, R.P., and H.S. Hudson, Solar Phys. **50**, 153, 1976.
54. Litvinenko, Yu.E., and B.V. Somov, Solar Phys. **158**, 317, 1995.
55. Mandzhavidze, N., and R. Ramaty, Ap.J. **396**, L111, 1992.
56. Martens, P.C.H., Ap.J. **330**, L131, 1988.
57. Mason, G.M., G. Gloeckler, and D. Hovestadt, Ap.J. **280**, 902, 1984.
58. Mason, G.M., J.E. Mazur, M.D. Looper, and R.A. Mewaldt, Ap.J. **452**, 901, 1995.
59. McAllister, A.H., M. Dryer, P. McIntosh, H. Singer, and L. Weiss, Proc. Third SOHO Workshop, ESA SP-**373**, 315, 1994.
60. Miller, J.A., and A.F. Vinas, Ap.J. **412**, 386, 1993.
61. Moses, D., W. Droge, P. Meyer, and P. Evenson, Ap.J. **346**, 523, 1989.
62. Munro, R.H., J.T. Gosling, E. Hildner, R.M. MacQueen, A.I. Poland, and C.L. Ross, Solar Phys. **61**, 201, 1979.
63. Reames, D.V., Proc. of the Third SOHO Workshop, ESA SP- **373**, 107, 1994.
64. Reames, D.V., H.V. Cane, and T.T. von Rosenvinge, Ap.J. **357**, 259, 1990.
65. Reid, G.C., and H. Leinbach, J. Geophys. Res. **64**, 1801, 1959.
66. Reinhard, R., and G. Wibberenz, Solar Phys. **36**, 473, 1974.
67. Sanahuja, B., A.M. Heras, V. Domingo, and J.A. Joselyn, Solar Phys. **134**, 379, 1991.
68. Smart, D.F., and M.A. Shea, J. Geophys. Res. **90**, 183, 1985.
69. Smart, D.F., M.A. Shea, and L.C. Gentile, AIP Conf. Proc. **294** (eds J.M. Ryan and W.T. Vestrand), 222, 1994.
70. Smith, Z., and M. Dryer, Solar Phys. **129**, 387, 1990.
71. Stolpovskii, V.G., G. Erdos, S.W. Kahler, E.I. Daibog, and Yu. I. Logachev, 24th ICRC (Rome) **4**, 301, 1995.
72. St. Cyr, O.C., and D.F. Webb, Solar Phys. **136**, 379, 1991.
73. Svestka, Z., and L. Fritzova-Svestkova, Solar Phys. **36**, 417, 1974.
74. Trottet, G., Sol. Phys. **104**, 145, 1986.
75. Tsuneta, S., T. Takahashi, L.W. Acton, M.E. Bruner, K.L. Harvey, Y. Ogawara, Publ. Astron. Soc. Japan **44**, L211, 1992.
76. Tylka, A.J., P.R. Boberg, J.H. Adams, Jr., L.P. Beahm, W.F. Dietrich, and T. Kleis, Ap.J. **444**, L109, 1995.
77. Van Hollebeke, M.A.I., F.B. McDonald, and J.P. Meyer, Ap.J. Supplement **73**, 285, 1990.
78. Vrsnak, B., V. Ruzdjak, P. Zlobec, and H. Aurass, Solar Phys. **158**, 331, 1995.
79. Wagner, W.J., and R.M. MacQueen, Astron. Astrophys. **120**, 136, 1983.
80. Wibberenz, G., and H.V. Cane, 23rd ICRC (Calgary) **3**, 274, 1993.
81. Zhang, L., J. Mu, B. Dai, and W. Zhou, 23rd ICRC (Calgary) **3**, 33, 1993a.
82. Zhang, L., B. Ai, Y. Feng, J. Mu, and W. Zhou, 23rd ICRC (Calgary) **3**, 37, 1993b.